Using NOGAPS Singular Vectors to Diagnose Large-scale Influences on Tropical Cyclogenesis

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LONG-TERM GOALS

The overarching goal is to improve our understanding of synoptic-scale influences on tropical cyclone (TC) formation and motion in the western North Pacific Ocean, in the context of error growth in forecast models. Benefits to the Navy would include improved forecast skill of the structure and track of developing and recurving TCs.

OBJECTIVES

The first objective is to connect Singular Vector (SV) and ensemble perturbation growth to synoptic-scale dynamical influences on tropical cyclone formation and structure change. The second objective is to extend these investigations towards vortex initialization and analysis of tropical cyclone structure in high-resolution models. The goal is to extend these methodologies into the Navy's COAMPS-TC framework.

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APPROACH

Ensemble-based sensitivities and predictability studies have been completed. The approach has been to investigate probabilistic predictions and perturbation growth from ensembles in the THORPEX Interactive Grand Global Ensemble (TIGGE), for cases from ONR's Tropical Cyclone Structure (TCS-08) field experiment.

The sensitivity patterns, evolving horizontal and vertical structure and error growth associated with Singular Vectors are also being investigated. The connection between perturbation structures and synoptic-scale processes influencing tropical cyclones is explored. Hypotheses for SV growth have been formulated by Munehiko Yamaguchi, the graduate student funded on this grant, using a barotropic model.

New vortex initialization methods based on theory and observations are being designed to provide superior representations of initial TC structure in high-resolution models than are presently achievable via data assimilation. The 2-km resolution version of the Weather Research and Forecasting (WRF) model is presently being used for this purpose, and the initialization code will be portable to COAMPS-TC at any time. Research on the sensitivity of numerical simulations to prescriptions of the initial vortex is ongoing.

WORK COMPLETED

Probabilistic track forecasts based on ensemble forecasts were evaluated and published in *Weather and Forecasting* (Majumdar and Finocchio 2010).

A study on the dynamics of SV-based perturbations in ensemble forecasts of Typhoon Sinlaku (2008) formed the bulk of Yamaguchi's M.S. thesis, and has been published in *Monthly Weather Review* (Yamaguchi and Majumdar 2010).

A related study examines the fundamental properties of SVs in TC-like vortices, using a barotropic model. It has been hypothesized that the structures and locations of SVs would be dependent on (i) initial profiles of the vortex, (b) the optimization time interval over which the SVs grow, (iii) the norm by which the SV growth is optimized and (d) the resolution of the model. These configurations are expected to be important in determining processes associated with error growth in models of TCs.

Finally, a new, flexible vortex removal and insertion scheme has been developed using the Weather Research and Forecasting (WRF) model. The rationale is to provide a vortex initialization scheme for use by the broad community, and to offer a benchmark upon which high-resolution data assimilation schemes must improve upon.

RESULTS

For the study on the dynamics of SV-based perturbations in ensemble forecasts of Typhoon Sinlaku (2008), it was first found that the structure and growth of SV-based perturbations differed substantially from those initialized using other methods. Furthermore, three mechanisms that explained the spreading of the tracks of Sinlaku were found. These were (i) baroclinic energy conversion in the vortex, (ii) baroclinic energy conversion associated with mid-latitude waves, and (iii) barotropic energy conversion in the vortex. For baroclinic energy conversion in the vortex, the temperature

perturbation is 90° ahead of the streamfunction perturbation, allowing the perturbation to obtain eddy available potential energy from the mean available potential energy (Fig. 1). This in turn leads to the modification of the steering flow and asymmetric propagation vector.

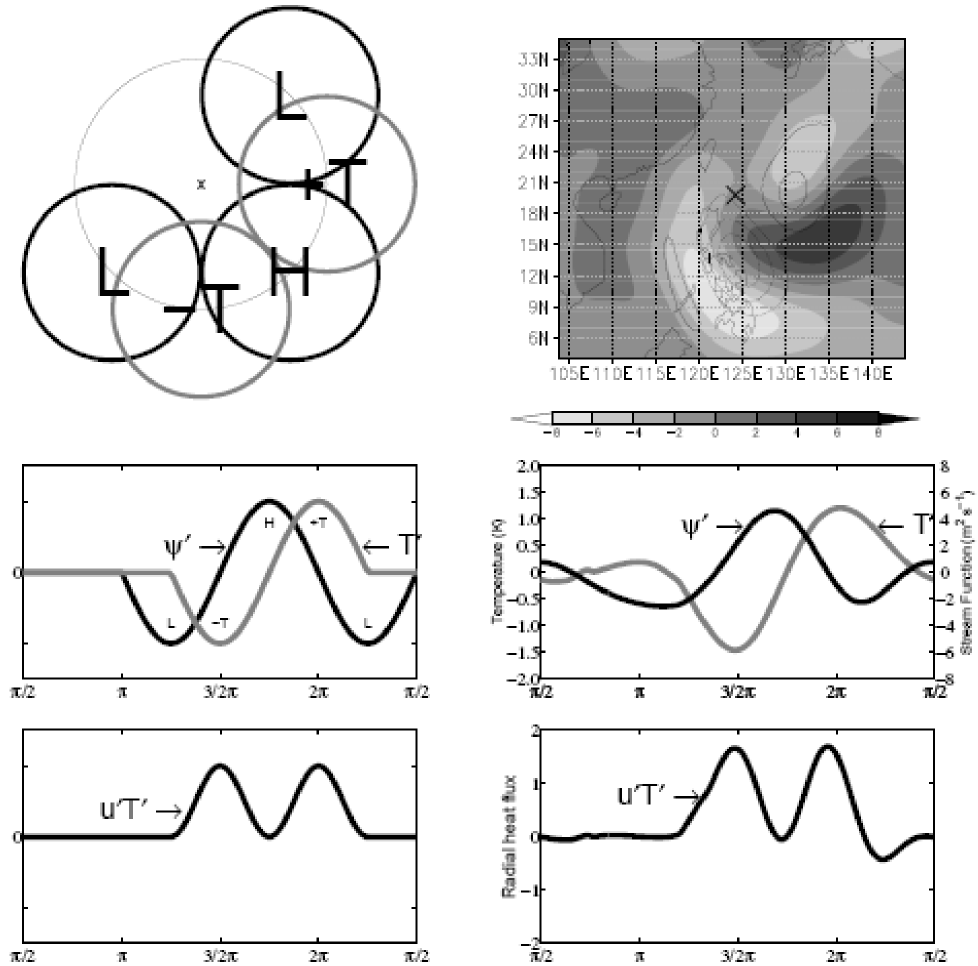

FIGURE 1. Left: schematic of streamfunction and temperature perturbations: (upper) centered on a TC-like vortex and (lower) plotted versus azimuth. Right: Initial perturbations of 500 hPa streamfunction (shaded, divided by 100000) and temperature (contours, every 0.5K, negative dashed, positive solid) in one ECMWF ensemble member for Typhoon Sinlaku on 0000 UTC 10 September 2008. The two lower right hand panels illustrate the corresponding azimuthal structures of streamfunction and temperature perturbation, and the radial heat flux 500 km from the center of Sinlaku.

In the barotropic model framework, it was found that the amplitude of the SVs increases with the maximum wind speed and decreases with the radius of maximum wind; that the location of SVs moves outward as the maximum wind, its radius and optimization time increases; and that viscosity plays a role in determining the azimuthal wavenumber of the leading SVs. An SV capturing barotropic instability of normal modes was identified. It was also found that the leading SVs computed on a β-

plane have a wavenumber one structure at the optimization time, suggesting the displacement of the vortex. The second SV represented an orthogonal displacement, thereby suggesting that the leading SVs are associated with along- and cross-track forecast errors.

For the vortex initialization study, examples of two synthetic vortices, constructed from ‘nature’ runs of (a) a tropical storm undergoing rapid intensification and (b) a Category-4 storm are illustrated in Fig. 2. Although the gross horizontal characteristics are simulated well, the vertical structure requires improvement given that the synthetic vortex is too deep at the radius of maximum winds.

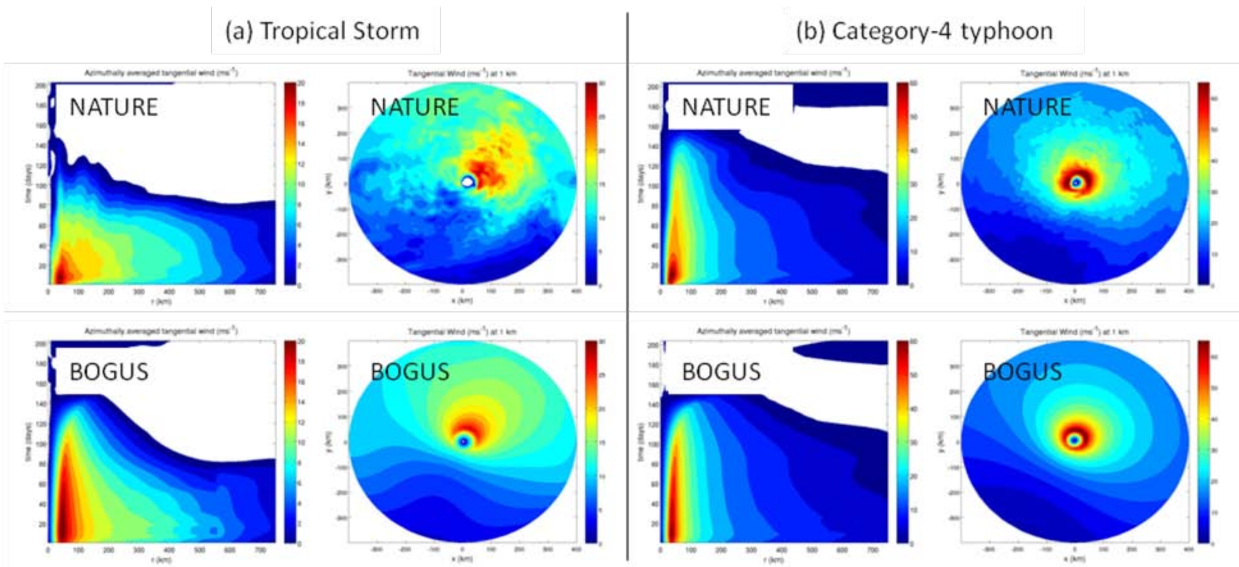

FIGURE 2. (a) Vertical and horizontal distributions of tangential wind in (top) the nature run and (bottom) the bogus vortex, for a vortex of tropical storm strength. (b) As for (a) but for a vortex of Category 4 strength. A 2-km resolution version of the Advanced Research WRF is used.

The 2-km resolution WRF simulations initialized using the blended initial conditions with the new synthetic vortex have yielded promising results for simulated storms of varying strength. The track forecasts with the new vortex were often indistinguishable from the simulated ‘truth’. The intensity changes through the forecast period were also captured adequately, although the peak intensity was not always reached. Only a perfect model framework has been used so far, and a more realistic imperfect model would yield larger errors. The purpose of the initialization so far has been to evaluate the fidelity of the initialization method and modify as required. This initialization technique with the primary circulation is nearly ready for transition to Navy collaborators.

IMPACT/APPLICATIONS

The scientific impact will be an improved understanding of the underlying environmental mechanisms that influence tropical cyclone formation. This understanding will be coupled with a quantitative knowledge of error growth in global models, via SVs and ensembles. The SVs also possess practical value in that they can be used in future targeting applications. High-resolution simulations and vortex initialization will be performed in collaboration with the COAMPS-TC team at NRL Monterey,

leading to improved Navy forecasts of TC structure. Finally, the global ensemble results will assist in the development of NOGAPS ensembles, and Navy consensus mean and probabilistic predictions may be improved via the use of global model ensembles.

RELATED PROJECTS

This project is related to that funded by the TCS-08 grant N000140810251: "Advanced Satellite-Derived Wind Observations, Assimilation, and Targeting Strategies during TCS-08 for Developing Improved Operational Analysis and Prediction of Western North Pacific Tropical Cyclones", on which Majumdar is a Co-PI. The NOGAPS Singular Vectors are also investigated in this grant. The high-resolution modeling and vortex initialization tools developed as part of this project are being used in the collaborative NOPP grant between the PI and CIMSS Wisconsin, NRL Monterey and NCAR, on assimilating satellite data to improve forecasts of TC intensity change.

PUBLICATIONS

Majumdar, S. J. and P. M. Finocchio, 2010: On the ability of global Ensemble Prediction Systems to predict tropical cyclone track probabilities. *Wea. Forecasting*, **25**, 679-700.

Yamaguchi, M. and S. J. Majumdar, 2010: Using TIGGE data to diagnose initial perturbations and their growth for tropical cyclone ensemble forecasts. *Mon. Wea. Rev.*, **138**, 1635-3655.

HONORS/AWARDS/PRIZES

The PI has recently been elected a Fellow of the Cooperative Institute of Marine and Atmospheric Science (CIMAS).